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I. INTRODUCTION

During the period September 1, 1977 to August 31, 1978, under Contract No. N66001-77-C-0348, the University of New Hampshire has been engaged in the development of technology relating to a micro-processor-controlled, unmanned free-swimming vehicle. The program is under the sponsorship of the United States Geological Survey, operating thru the program leadership of the Naval Ocean Systems Center (NOSC).

Underwater pipeline and structure inspection missions are of direct concern to the U.S. Geological Survey's (USGS) research and development program in pollution prevention and safety in outer-continental shelf oil and gas operations. Unmanned, un-tethered submersible systems have a significant potential for up-grading the scope and efficiency of these inspection missions in a cost-effective manner. Consequently, the best interests of the USGS program are served by developing the technology required to achieve the full potential of these systems.

Under a student-faculty program, an open frame submersible, capable of motion with five degrees of freedom, was constructed at the University. The potential of applying such a class of vehicles to a range of useful underwater work tasks, once intelligence were placed on board, soon became apparent. Under USGS leadership, a vehicle mission of acquiring and following an exposed pipeline was devised and a program of technology development established.

Five project goals were established for the period covered by this report as detailed further in Appendix B. They are:

1. To develop operationally reliable hardware and software.
2. To develop a vehicle control console.
3. To provide external access to the on-board microprocessor (for software program modification).
4. To perform an evaluation of the strengths and weaknesses of the first generation system.
5. To develop technology sharing with the Naval Ocean Systems Center.

The program evolved toward these goals through several major stages:

1. Vehicle hardware was developed and tested.
2. A range of software programs were developed and tested.
3. The vehicle was placed in Lake Winnipesaukee, and a series of tests were run.

This report focuses on several key elements of this program including a description of the vehicle and a review of the sonar sensor system, plus considerable attention to the computer and its software. The field tests are described and their teachings outlined. The report then proceeds to summarize our learnings from the year's work and our perceptions of the potential for the intelligent unmanned autonomous vehicle for the USGS mission.

A collateral effort that took perhaps 10% of the year's effort was the writing of a "Technology Development Plan", a working document prepared in cooperation with NOSC, for the United States Geological Survey Research Program in OCS Oil and Gas Operations. Its bustitle is "Unmanned, Untethered, Submersible Systems for Inspection Missions."

Under the leadership of the Naval Ocean Systems Center, a multi-year program concept had evolved which related many of the various technology potentials involved with these vehicles, and examined their orderly growth and development. This background material was then placed in the environment of the mission and was organized as a formalized Technology Development Plan. Some 24 related areas of technology potential and opportunity were described. The missions which were studied, relate to the responsibilities of USGS, and thus the document obviously does not exhaust the potential for the unmanned untethered small submersible.

II. THE VEHICLE

The UNH vehicle, as configured for the pipe-following task, is shown in Figure 1.

The structural system is seen to include the frame, battery and electronics containers, the buoyancy structure and the transducer ring. Choice of the vehicle's open frame invites a comparison of shell-frame and open-space-frame systems. Shell frame systems are necessary, of course, to provide for the streamlining of relatively high-speed vehicles, to guard against entanglement with external objects and to protect items within the shell's envelope. Since the design objectives of this program do not demand high speed and since man's exclusion from the vehicle system reduces the impact of entanglement, an open-space-frame system becomes worthy of serious consideration despite a lessening of protection for on-board items. This shortcoming is more than balanced by providing greater flexibility in the location and orientation of thruster units and other equipment. Due to the removal of shell plating and a resulting lowering of hydrodynamic forces and moments, maneuvering at low and zero speeds is facilitated. Consequently, we have chosen an open-space-frame system for this vehicle. The system, as shown in the referenced figure, is considered to be the most satisfactory of four different frame configurations evaluated for strength and ease in arranging on-board items to best meet the design requirements. It consists of 1.0" O.D., 6062-T3 aluminum tubing with 0.25" aluminum plating being used for corner brackets and mounts for the containers and buoyancy structure. The entire frame is coated with epoxy paint to inhibit corrosion.

Two box-shaped battery containers are located on the port and starboard sides of the vehicle near the baseline so that the eight batteries they house will lower the vehicle center of gravity. They are made of 0.75" plywood covered with fiberglass, the bottom joints being reinforced with two-inch angle irons. The lids are sealed with flat neoprene gaskets, while electrical and air connections to the containers are made through aluminum plates embedded in them. Internal-external pressures on the containers are equalized by a high-pressure air system thus obviating the necessity for heavy, pressure-resisting shell structures and elaborate, costly seals.

The electronics container is located on the vehicle's centerline as high as feasible so that its positive buoyancy will contribute to a relatively high center of buoyancy for the system. This location, external to the frame, also facilitates accessibility of electronic components. The container is an 8.0" I.D., 0.5" thick, 606-T6 aluminum cylinder closed by 0.75" thick aluminum hemiheads fitted with O-ring seals. All electronic connections are made through these hemiheads.

Two buoyancy structures are required to give the vehicle 11.69 pounds of positive buoyancy in the submerged-trim condition, thereby providing for fail-safe operation. These structures are located at the top of the frame, port and starboard of the electronics container, resulting in a high center of buoyancy. They are constructed of 10.0" O.D. cardboard cylinders filled with urethane foam and covered with fiberglass, this type of structure having a weight/displacement ratio of 0.14.

The transducer ring, located at the base of the vehicle below the frame, supports a circular array of twelve transducers. The ring is 5.0 feet in diameter and is made of flat-bar stock.

The vehicle's energy storage system consists of eight automobile batteries, four in each of the port and starboard battery containers. These batteries supply all of the electrical energy for propulsion, maneuvering, and electronic equipment supply. Their 7.5 kilowatt-hour capacity provides a mission endurance of four to five hours under average conditions. The placement of this much power on board the vehicle is made necessary by the free-swimming and ultimate autonomy requirements which rule out power transmission from a remote energy source.

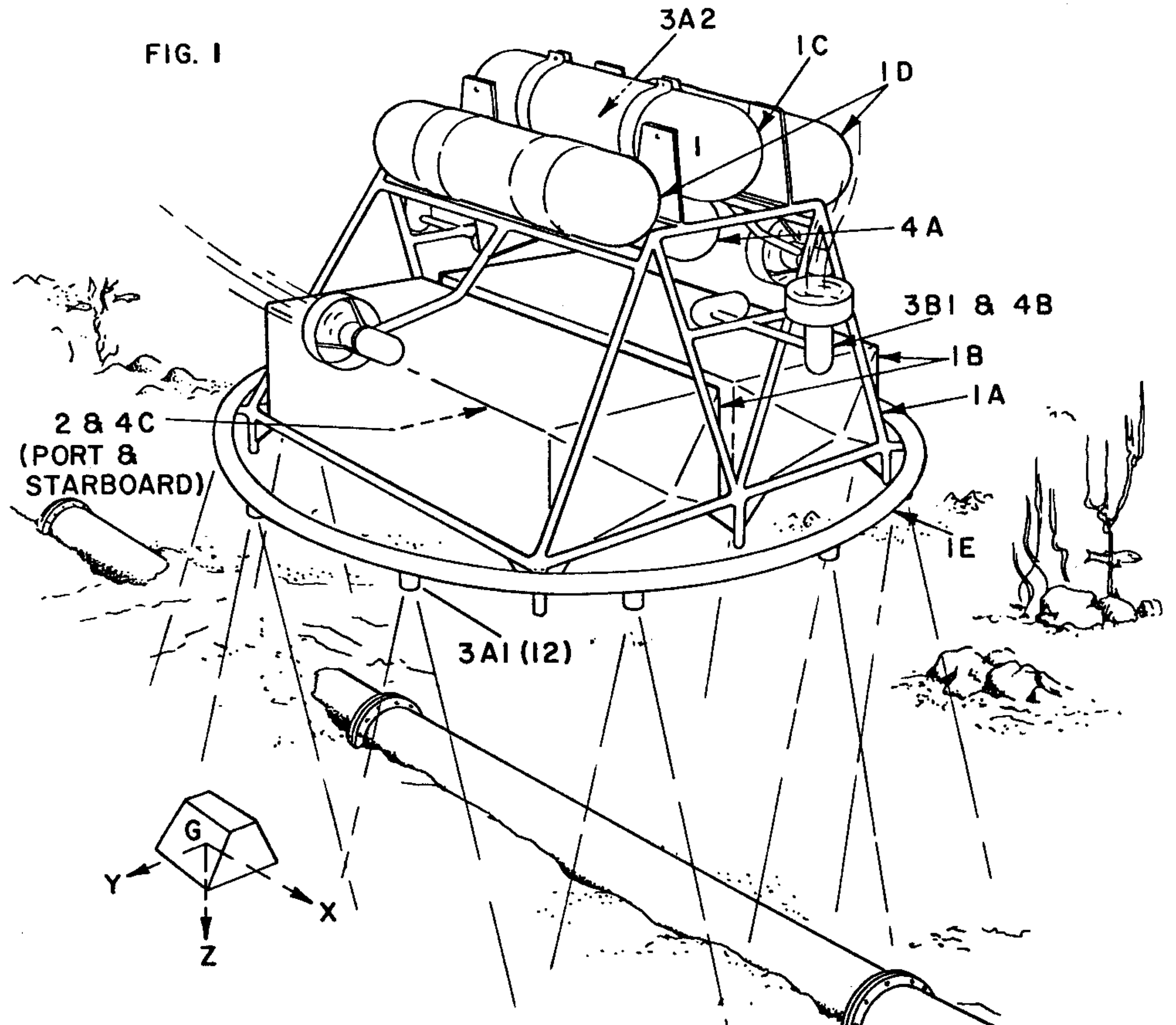
Propulsion and maneuvering control decisions are executed by electric motor/screw-propeller, thrust-producing units, each unit having motor and thrust ratings of 0.25 horsepower and 17.0 pounds respectively. Motor casings are oil compensated. The vehicle is propelled by two units providing a total thrust of 34.0 pounds.

This thrust is sufficient to obtain speeds of 1.6 knots against zero current velocity of 0.6 knots against 1.0 knot currents, a capability which meets the targeted performance requirements. Maneuvering must be accomplished entirely by these thrust-producing units since moveable control surfaces are useless at the required low speeds, and simplicity dictates exclusion of variable ballast, trim and list static control systems. Six motor units, including the two for propulsion, are positioned in the x, y, and z - axes directions as indicated in Figure 1 to provide the five degrees of freedom in motion control necessary for meeting the performance requirements. There is no requirement for the sixth degree of freedom; roll or list about the vehicle's x-axis, since a vertical separation of the centers of buoyancy and gravity of 0.70 feet assures positive stability. It should be recalled that the vehicle possesses 11.69 pounds of positive buoyancy in the submerged-trim condition which, of course, necessitates compensating thrust from the two z-axis directed units to achieve depth control. A finer degree of control of depth may be obtained with this approach than by maintaining a neutral buoyancy submerged-trim condition. Additionally, this method avoids raising silt clouds due to downward-directed water particles to obtain upward thrust, a distinct advantage if a mission should ever require on-board television equipment.

The hardware system employed in the electronics is indicated in Figure 2, the system wiring diagram. The problems of system construction, involving a substantial portion of the years work are summarized in this chart, without detail. Printed circuit boards, labeled CPU (Central Processing Unit) are indicated by empty blocks to keep the diagram manageable. The details are available on request, thus sparing the generalist reader. It will be noted that functions are reserved to plug-in boards which interface through a common bus, permitting all elements to inter-communicate. This technique permits interchangeability and further expansion as required.

UNH VEHICLE

FIG. I



VEHICLE SYSTEM

I. STRUCTURE
- IA. FRAME
- IB. BATTERY CONTAINERS (2)
- IC. ELECTRONICS CONTAINER
- ID. BUOYANCY STRUCTURE
- IE. TRANSDUCER RING

2. ENERGY STORAGE

3. PROPULSION – MANEUVERING
- 3A. VEHICLE CONTROL (DECISION MAKING)
  - 3AI. SENSORS
  - 3A2. MICROCOMPUTER
- 3B. VEHICLE CONTROL (DECISION EXECUTING)
  - 3BI. MOTOR-PROPELLER UNITS

4. AUXILIARY SYSTEMS
- 4A. COMPRESSED AIR
- 4B. OIL COMPENSATION
- 4C. HYDROGEN ABATEMENT

SYSTEM WIRING DIAGRAM

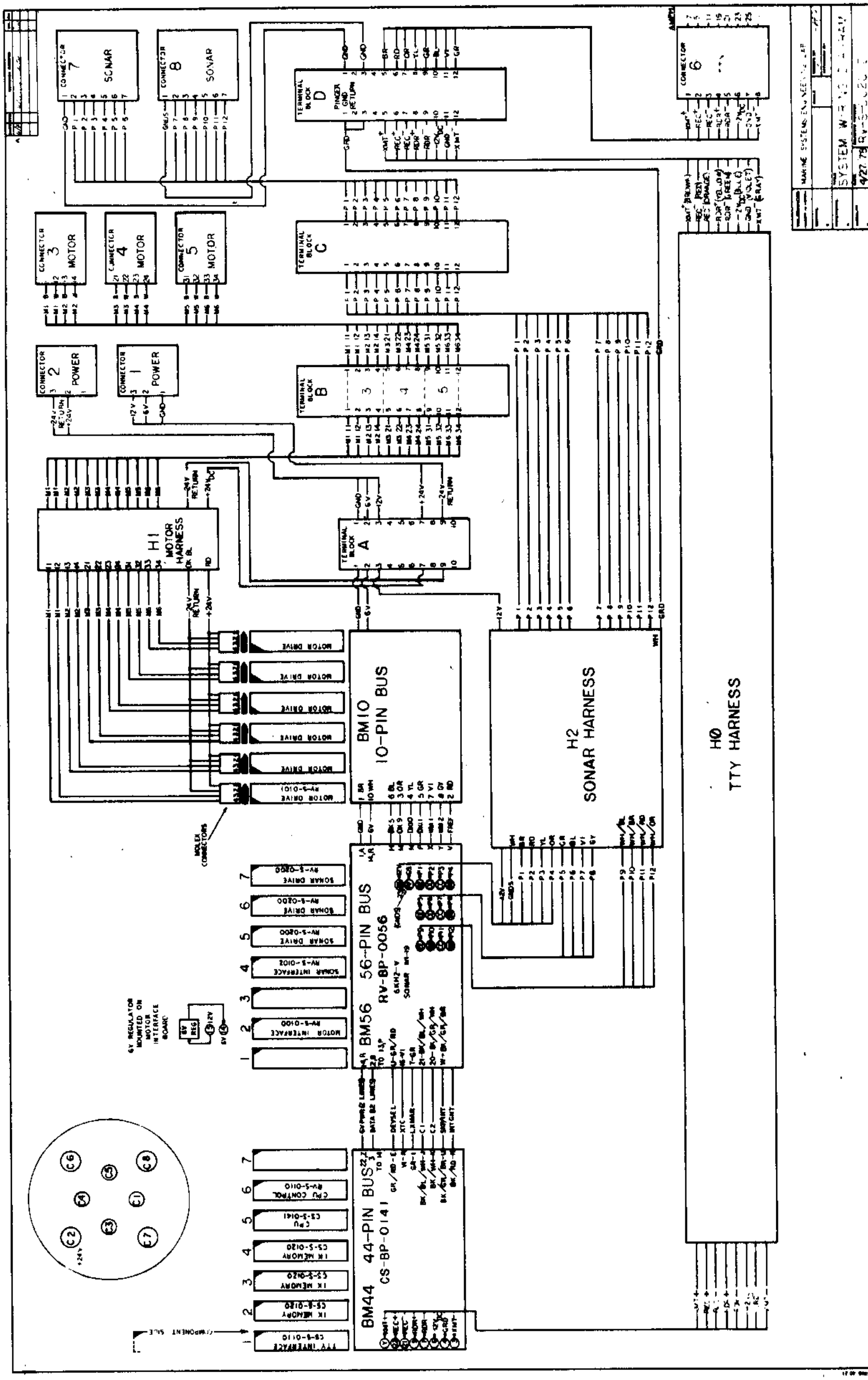


FIGURE 2

III. THE SONAR SYSTEM

The sonar system is constructed around a sensor that includes twelve transducers equally spaced around a ring 60 inches in diameter. Each is pulsed sequentially and echoes return from the sea floor below. If an exposed pipeline is within view of the sensors, appropriate channels will exhibit shortened echo paths. For example, if the vehicle is astride the pipe and aligned with it, the sensors at 6 o'clock and 12 o'clock around the transducer ring will experience shortened echo paths.

The sensor patterns will overlap, and thus system gains must be controlled by the computer to achieve maximum target discrimination. Maneuvers to acquire the pipe and subsequently to follow it requires a sophisticated set of data manipulative algorithms. To guard against false indicators from surface irregularities, substantial data averaging must be incorporated. These questions, addressed in a subsequent chapter, illustrate how a system design that once would be considered a hardware problem has now become a software question, and is now a matter of manipulating of concepts rather than simply of physical devices.

IV. THE MICROCOMPUTER

The computer as a system controller, is central to the vehicle's self-controllability - possessing a capability to make control decisions and to give control commands to the vehicle's thrust-producing system for execution based on sensed inputs and stored logic patterns. The vehicle's microcomputer system, diagrammed in Figure 3 is built around the 6100 microprocessor.

This microprocessor was chosen among literally hundreds of candidate central processing units for two leading reasons. It is of CMOS construction, and thus draws an extraordinarily small amount of DC Power. Computer power demands, of course, are small when compared with thruster power requirements. It was not known, however, when an assignment might require long periods of quiescent sea floor operation where the computer drain then might have an important impact on the power budget. The instruction set, moreover, is identical to that of the long available PDP-8, and its use obviously saves programming training, permits use of proven diagnostics, and easy transfer of available software. The 6100, a 12-bit machine, is a little less sophisticated than some modern competitors, but its competence is more than ample for the tasks associated with this vehicle, and perhaps for the vehicle that may follow it.

The microprocessor system is designed so that a single bus structure provides access to all components of the computer and, as such, permits use of a modular design concept which will accept additional function blocks with an absolute minimum of hardware change. This concept is necessary due to the evolutionary nature of a program where frequent system alterations and advances occur based on ever increasing experience with the system.

The microcomputer system may be divided into three functional areas:

1. The microprocessor with associated control and memory including the serial interface
2. The sonar interface system
3. The motor control interface system

Area (1) contains the central processing logic as well as the control logic necessary to achieve physical responses. Areas (2) and (3) are concerned with the actual control of the vehicle in performing its task of locating and following, at a predetermined height over an exposed pipeline, and of conducting the various support maneuvers.

The microprocessor and associated systems contain both ROM and RAM solid-state memory fields. Included in the hardware is a serial interface which allows remote-operator access to the computer system when a light-weight cable is attached to the vehicle for system checkout or monitoring. This interface and the associated software programming permits the full capability of the PDP-8 ODT (octal debugging technique) system to be used.

The sonar interface system connects all twelve of the individual sonar systems (transducers) mounted on the transducer ring to the computer. The hardware structure of this interface also allows program control over specific test and calibration procedures. The interface is essentially a sixteen port, digital I/O device with on-card timing and control. The function of the sonar system is to provide vehicle control information to the microcomputer system whose output, in turn, directs the vehicle in accomplishing its mission tasks. The sensor system chosen for this application consists of twelve separate sonar systems (Massa model R283E transducers) mounted in a clocklike configuration on the transducer ring, and eighteen-pin integrated circuit and associated components. Advantages of this modular approach include its low cost, minimal external circuitry for each sonar system, low power dissipation, high reliability and ease of interfacing with the microcomputer system.

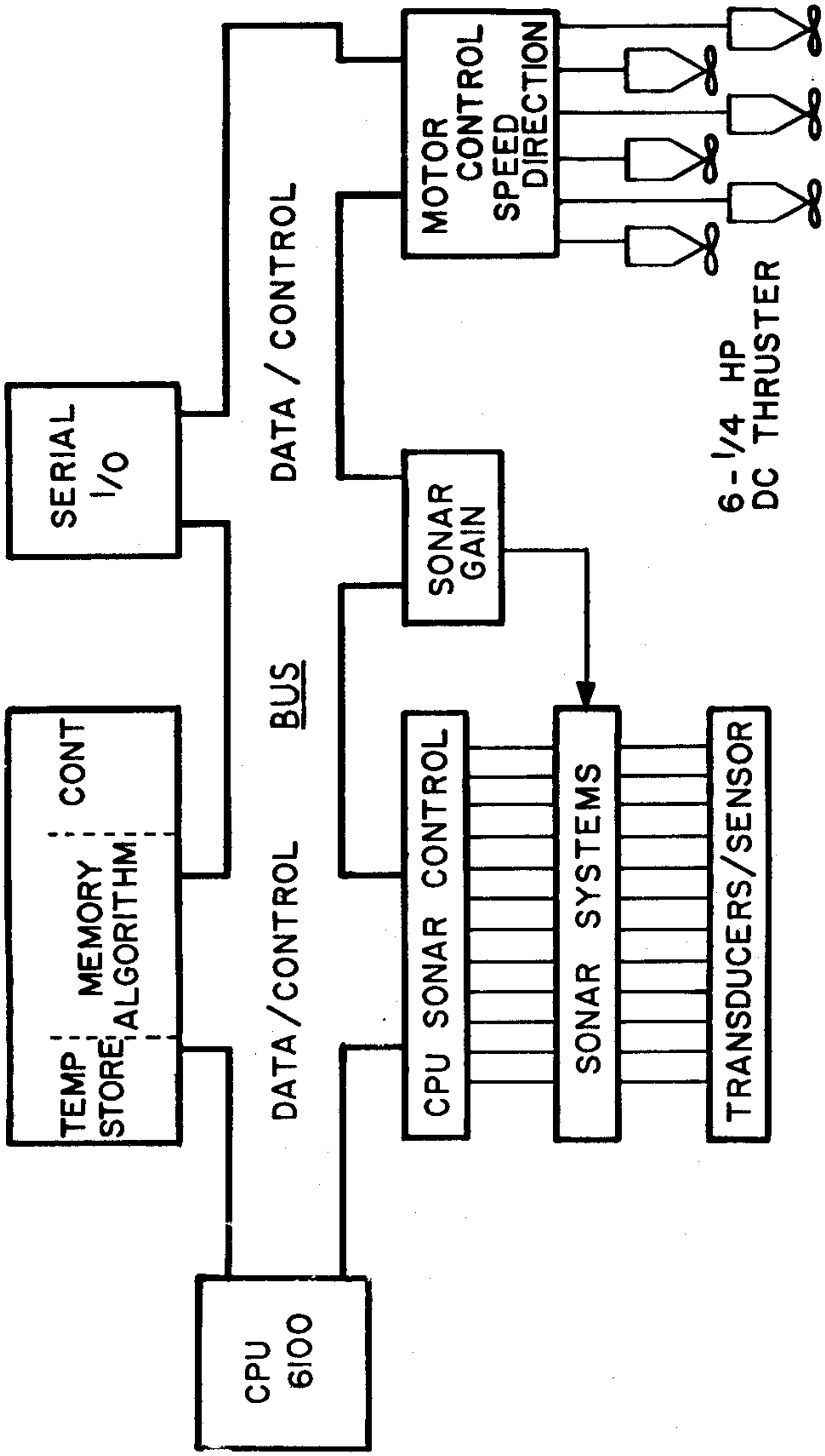


FIG. 3 *MICROCOMPUTER SYSTEM BLOCK DIAGRAM*

A. The Computer as a Sonar Data Processor

There are problems inherent in sonar systems which must be considered in a pipe-following program. Reflection of the acoustic signal from one transducer may be interpreted as the return signal of another transducer. Moreover, the vehicle may pass over a less-than-ideally flat bottom -- a bottom strewn with rocks, debris, and other objects which may cause incorrect vehicle-bottom distance readings. Consequently, it is important to the decision-making process to be able to employ a criterion capable of differentiating between correct and false readings. A digital gain control feature of the sensor system along with the microcomputer system and associated software accomplishes this differentiation. If a reading is determined to be false, the gain of that transceiver may be altered so as to eliminate the false returns. This is done by latching a new, four-bit, gain-control word into the D/A converter which, in turn, alters the voltage applied to a set of FET's used as voltage variable resistors (VVR). It is this resistance which sets the gain of a particular transceiver circuit. The four-bit word thus allows sixteen, (2^4), levels of gain. Four specific sequences are used to control the operations as follows:

1. Specific sonar system address, transmit and receive
2. Vehicle altitude control
3. Variable detection window operation
4. Timing accuracy self test

These regimes are further described below.

The first function performed by the sonar interface provides for the interrogation of each of the twelve sonar systems on the transducer ring. The sonar and motor interface control systems are similar in that a four-bit word is used to decode input and output ports of the I/O device. The sonar interface uses a one-of-sixteen decoder to direct a transmit pulse out to a specific sonar system and then to open a specific input channel to the control and timing circuits of the interface. As only twelve sonar systems comprise the sensor, four channels may be used for unrelated program tasks. One of the spare channels is used for a timing self-test.

The second function of the sonar interface is to determine vehicle altitude and to transfer this information to the computer. A specific sequence of events occur to accomplish this function. They are: (1) A program instruction latches a four bit address into the sonar interface, this address connecting the input and output of a specific sonar system to the timing components of the interface. (2) A second instruction resets the counting electronics and initiates a fifty μ-second transmit pulse. (3) When the return pulse is received, the timing count is stopped and held in a register on the sonar interface. This count, representing the vehicle's altitude, can now be brought into the computer as needed - either to be compared with a preset number, to determine vehicle altitude with respect to a preset altitude, or as data itself to be used as a preset altitude for future comparisons.

A third function of the sonar interface is to set up a detection window in such a manner that a valid return pulse will occur only when the window is active. If the return pulse occurs at a different time, it is assumed that a false return has been received and it will be ignored. The detection window time can be set under program control to be active for varying lengths of time or it can be held active continuously which, in effect, voids the detection window function of the interface.

A fourth function of the sonar interface is assurance of proper operation by a self-check system. This system's sequence allows the software system to generate a series of two pulses which simulate an outgoing transit pulse and a return echo. The time between the two pulses is accurately known and can be compared to the time determined by the interface hardware to be the two-way travel time of the simulated acoustic transmission. This comparison insures the proper operation of the interface.

B. Computer Thrust Control

The motor control interface system determines the speed and direction of the DC motors of each of the six thrust-producing units. The motors are individually controlled by program instructions in the form of a four-bit motor control word which determines one of eight specific speeds, (2^3), and forward or reverse, (2^1). During the motor instruction sequence, the four-bit word is placed in a four-bit latch. This word remains in the latch until updated speed and forward or aft direction is called for by the control program.

The motor speed control is a pulse-width modulation system which is computer controlled so that the frequency of the drive signal applied to each motor is chosen from one of eight drive frequencies. These frequencies are generated by a master clock that has been divided down using a multistage counter having eight different outputs available. The frequencies are then used as inputs to a one of eight decoder. When the first three bits of the motor control word are used to address the decoder, a specific frequency is available for the motor-drive circuitry. The motor direction is set by the fourth bit of the motor control word which determines the polarity of the applied drive voltage.

C. Other Computer Functions

Although this report describes what the system does, it is worthy to pause and consider what it might do. The microprocessor is capable of addressing 32K of memory, and it processes a command in a time span of only a few microseconds. The program that controls the vehicles motion, that processes twelve sonars and that does the necessary house-keeping requires no more than 4K of the potential 32K memory. The skills demonstrated by today's vehicle thus demands only about 10% of the computer's capability. Many microprocessors now cost less than $10.00, so that there is no small limit to the effective intelligence that may be placed in the vehicle, at minimal cost indeed. This implies that the multiprocessor concept, the cooperative interaction of a set of dedicated microprocessors to accomplish very sophisticated tasks is entirely applicable to a future, still inexpensive, vehicle. It also implies that tasks of an order of magnitude increase in sophistication may be accomplished with the one central processing unit now on the computer.

V. SOFTWARE

A. General Description

The software for the Experimental Autonomous Vehicle, developed at the University of New Hampshire, consists of four major groups of programs written in machine and assembly language for the 6100 microprocessor. The programs are loaded into random access memory and serve either to control the vehicle in the autonomous mode or to allow an operator to control the vehicle by means of a terminal connected to the on-board computer by a tether, or subsequently by acoustic command link. The four major program groups are:

1. Thruster Interactive Diagnostic Routines
2. Pipefollower Programs
3. Maneuvering Programs
4. Trackline Printout

These are each described in their functional details. Their flow diagrams are included in Appendix A. Copies of machine language printouts and written descriptions of the flow diagrams are not included, for space reasons, although the sub-routines are named in the descriptions below. Correspondence is invited on the details of these programs.

1. Thruster Interactive Diagnostic Routines

A. General

The Thruster Test Programs allow the operator to test the operation of the six thrusters and their seven speeds forward and seven speeds reverse.

The Thruster Test Programs are:

Thrus 2, A, S

B. Operation

Upon execution of the programs, the routine will wait for the operator to hit any TTY key and as soon as this is done, it will print the introductory instructions. The operator may then choose one of three command instructions as follows:

Type "A" - The Program will run through an automatic thruster test sequence starting with thruster number one and going through all seven speeds from maximum forward to maximum reverse for all six thrusters. If any TTY key is hit during the sequence, the thruster will shut off and control will jump to ODT.* Upon completion of the sequence for each thruster, the program will ask the operator if he wishes to test full power reverse and wait five seconds for any TTY key to be hit. If no key is hit, the program will continue testing the next thruster.

Type "S" - The Program will ask the operator which individual thruster he wishes to test and at what speed. The user may then increment the speed by typing "I", decrement the speed by typing "D", or enter a new speed. If the operator types "S", the thruster being tested will shut down and control will return to ODT.*

Type "X" - The Program will send control to ODT.*

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*ODT - Octal Debugging Technique.

2. Pipefollower Programs

A. General

The pipefollower programs will allow the vehicle to search for, position itself over, and follow a submerged pipeline. There are also provisions for manual control through a tether and a search routine in the event that the pipeline is lost. The pipefollower programs are:

VAR, KEYHIT, FOLOWR, XDUCER, ALTUDE, WHERE, STEER, AVERAG, SLIDE, LRTURN, UPDWN, FORBAC, MES, PRINT, DIRECT, REG, COMMON.

B. Operation

Upon execution, the programs will ping each sonar transducer two times, and a running total of the two-way times is kept. If there occur four bad readings at a certain gain, the gain is raised to the next higher gain, up to fifteen gain levels. If all fifteen gains give bad data, the vehicle will give a five second downward thrust and will repeat the sequence until good data is obtained.

The average of each transducer total of two-way times is taken and an average of all twelve transducer averages is created to form an average of averages. The average of averages is then compared to a special register containing the two-way sonar time for the desired operational altitude of the vehicle. The vehicle will attempt to maintain this altitude for the duration of the mission.

When the proper altitude is obtained, the vehicle will go forward at slow speed while still pinging the sonar transducers.

Each individual average is then compared to the average of averages and if the individual average is smaller by a "buffer amount", it is assumed that the pipeline is under that transducer. At the time the pipe is first found, a flag is set that sends the vehicle through a circular search pattern if the pipe is later lost. Each time that it is determined that the pipe is under a particular transducer, a bit is set equal to one in a special register in computer memory. By examining this register, the program is able to determine the location of the pipe and to make appropriate course connections by powering selected thrusters. The program will attempt to locate the pipeline directly under the front and back transducers.

When the vehicle is connected by the tether to a teletype, the operator may navigate the vehicle at any time by typing in the following commands:

"F" - Go Forward	"L" - Turn Left
"B" - Go Back	"R" - Turn Right
"U" - Go Up	"X" - Slide Left
"D" - Go Down	"Y" - Slide Right
"O" - Go To "ODT"	"X" - Stop All Thrusters

This is followed by the speed number desired.

"0" - Shut down the appropriate thruster.

Example: "F0" will shut down the forward thrusters.

"1" - Set the appropriate thrusters to slow speed.

"2" - Set the appropriate thrusters to medium speed.

"3" - Set the appropriate thrusters to fast speed.

An "L" or "R" can only be followed by a "1", "2", or "3", but not "0". If any key is struck while the vehicle is making a left or right turn, all thrusters are shut off and control goes to "ODT". This serves as an emergency stopping routine.

The vehicle will then execute the command until the operator types any character on the teletype. This releases the vehicle from operator control and returns control to the autonomous program sequences.

3. Maneuvering Programs (See Figure 4 - Thruster Orientation)

A. General

The maneuvering programs allow the operator to maneuver the vehicle by typing various commands on a teletype. Communication with the on-board computer is accomplished by means of a multi-channel cable tether, with acoustic telemetry under development.

The programs may be implemented in two distinct ways as determined by the specific programs loaded into computer memory. In the first, the vehicle will seek and maintain a predetermined altitude above the bottom while responding to operator maneuvering commands. This is referred to as the "auto-altitude" mode.

The specific programs used for maneuvering the vehicle with the auto-altitude mode are:

TMAIN, AUTO, SLIDE, LRTURN, UPDWN, FORBAC, DIRECT, REG, COMMON, PRINT, MES.

In the second case, the vehicle will respond solely to operator maneuvering commands with no altitude seeking provisions.

The specific programs used for maneuvering the vehicle without the auto-altitude mode are:

OLDTM, SLIDE, LRTURN, UPDWN, FORBAC, DIRECT, REG, COMMON, PRINT, MES.

B. Operation

Upon execution of the programs with the auto-altitude mode included, a single, selected transducer is pinged eight times and a running total of the two-way times stored in computer memory. If there occur four consecutive bad readings at a certain gain, the gain is raised to the next higher gain, up to fifteen gains. If no good data are obtained at the highest gain, the vehicle will execute a five second downward thrust to decrease the altitude of the vehicle above the bottom, and will repeat the sequence starting at the lowest gain until good data is obtained.

When eight good data sets are obtained, the average is calculated and compared to a predetermined two-way time for the desired operational altitude. This comparison will generate the proper thruster response to correct the vehicle's altitude.

At any time, the operator may maneuver the vehicle by typing the appropriate commands on the teletype as follows:

"F" - go forward	"L" - turn left
"B" - go back	"R" - turn right
"U" - go up	"X" - slide left
"D" - go down	"Y" - slide right
"O" - to to "ODT"	"X" - stop all thrusters

This is followed by the speed number desired.

"0" - shut down the appropriate thruster.

Example: "F0" will shut down the forward thrusters.

"1" - set the appropriate thrusters to slow speed.

"2" - set the appropriate thrusters to medium speed.

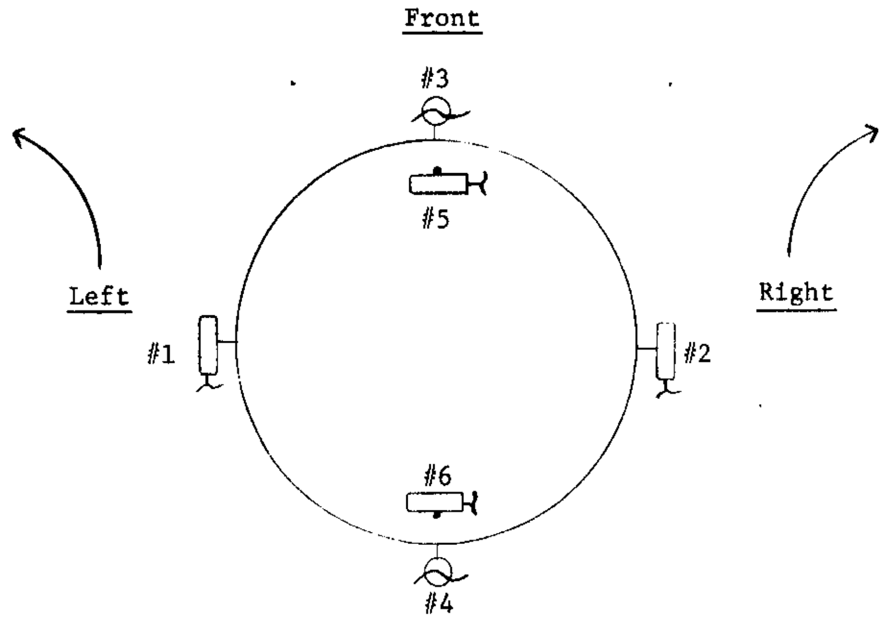
"3" - set the appropriate thrusters to fast speed.

An "L" or "R" can only be followed by a "1", "2", or "3", but not "0". If any key is struck while the vehicle is making a left or right turn, all thrusters are shut off and control goes to "ODT". This serves as an emergency stopping routine.

The system will execute the operator maneuvering commands until the operator hits any teletype key releasing it to return to the auto-altitude mode.

Upon execution of the programs without the auto-altitude mode, the vehicle will respond to the operator commands only and will make no independent altitude corrections.

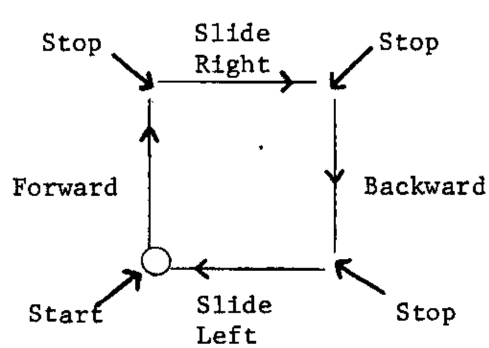
THRUSTER ORIENTATION



Thrusters #1 & #2 are used to move the vehicle forward or backward, and also to turn the vehicle left & right.

Thrusters #3 & #4 are used to move the vehicle up or down.

Thrusters #5 & #6 are used to slide the vehicle to the left or right.



SQUARE

Figure 4

4. Trackline Printout

A. General

The trackline printout programs will allow the vehicle to dive to a specified altitude above the bottom and go forward while taking sonar readings. The readings are stored in computer memory. When a specified number of readings have been taken, the vehicle will surface and use the data obtained to print a profile of the bottom.

The trackline printout programs are:

TMAIN, SONAR, PIN62, PICTUR, DIRECT, REG,
COMMON, PRINT, SLIDE, LRTURN, UPDWN, FORBAC.

B. Operation

Upon execution of the trackline printout programs, a single selected transducer is pinged eight times and a running total of the two-way times is stored in the on-board computer memory. If there occur four consecutive bad readings at a certain gain, the gain is raised to the next higher gain, up to fifteen gains. If no good data are obtained at the highest gain, the system will execute a five second downward thrust to decrease the altitude of the vehicle above the bottom, and will repeat the sequence starting at the lowest gain until good data is obtained.

When eight sets of good data are obtained, the average is calculated and compared to a predetermined two-way time for the desired operational altitude. This comparison will generate the proper thruster response to make the desired altitude corrections.

When the desired altitude is obtained, the programs will cause the vehicle to power at slow speed while pinging the transducer. 512 samples of data are then taken in 64 groups of 8. Each data set of 8 readings is inserted into the low end of a storage array after older data sets are pushed upward. After each data set is obtained, the program will make an altitude correction. When all 64 data sets are obtained, the vehicle will surface, and at the same time process the data into printable form. This is done by forming an average for each data set of 8 readings. This average is subtracted from each of the 8 readings in its data set. The result of each of the subtractions is then divided by 7 and placed back in the original location in the storage array. When the array has been fully processed, the program will print the array on the teletype terminal. Variations in elevation above the bottom, such as a pipeline, may then be easily observed.

If a tether is used, the processing and printout will begin as soon as the storage array is full, indicating that all data has been received. In addition, operator maneuvering commands may be used at any time to navigate the vehicle. These are described in sections dealing with the maneuvering programs.

When no tether is used, the processing and printing routines will wait for an operator command. This allows time for the tether to be connected.

VI. SYSTEM SPECIFICATIONS

The specifications for the UNH Vehicle, as it was prepared for the 1978 Field Tests were as follows:

Overall Dimensions	
Length x Breadth x Height	5'0" x 5'0" x 3'5"
Displacement submerged	824.92 Pds.
Weight	813.23 Pds.
Positive Buoyancy	11.69 Pds.
Payload*	0.00 Pds.
Statical Stability (BG)	0.70 Ft. (POS)
Speed (Max - No Current)	1.60 Knots
Power (At Max Speed)	0.50 H.P.
Maneuvering (Thrust/Moment)	
X - Axis (Surge)	34.0 Pds.
Y - Axis (Siddle/Pitch)	34.0 Pds./136.0 Ft. Pds.
Z - Axis (Depth Control/Yaw)	34.0 Pds./85.0 Ft. Pds.

* Payload = "Mission Equipment" for pipeline survey and monitoring. Space frame can easily carry buoyancy packages supporting 100 Pds. payload when on board.

VII. OPERATIONAL TESTING

The University of New Hampshire maintains a Test Facility at Diamond Island, at Lake Winnipesaukee, NH. During the summer quarter, ample student labor is available, and it was during this period June 18 to August 31, 1978, that the bulk of the system development and evaluation was accomplished.

A. Goals for evaluation

Five project goals culminated in the field tests at Lake Winnipesaukee. These were:

1. To develop operationally reliable hardware and software by careful attention to packaging and interface control.
2. To develop a vehicle control console through which the various vehicle functions are easily implemented. To implement the control functions, through the tether cable, at a data rate which could be duplicated by an acoustic data link.
3. To develop the necessary hardware and software to make external access to the on-board microcomputer possible.
4. To perform a total evaluation of the first generation pipe follower vehicle to determine its limitations and what may be done to minimize these limitations, and to document the vehicle and the test results in a manner which would allow easier development of a possible second generation vehicle.
5. To develop a technology sharing system between the Naval Ocean Systems Center and the University of New Hampshire in keeping with the collaborative nature of the program.

B. The System Tests

The following tests were established to determine system performance:

1. Sub-System Tests

a. Thruster Evaluation, to determine:

- generated thrust
- system time constants
- precision of course maintenance
- effectiveness of speed tracking between cooperating thrusters

b. Sonar System Evaluation, to determine:

- system acoustic travel time delays
- effective resolving power of the sonar
- effectiveness of the averaging algorithm
- consequence of convolved or rocky bottom on averaging process

c. Interactions of Hardware, Software, and the Operator

- does the software properly control the system
- to what degree is operator surveillance and control necessary
- is operator monitoring of system performance convenient and effective
- is the software design adequate for the assigned vehicle tasks

2. Operational Tests

A set of maneuvers have been assigned, as software routines to the vehicle, to evaluate its performance under a variety of conditions. They include:

a. Maneuvering tests

- straight line
- circle
- square
- cube (3 dimensional)

Measurement of effectiveness to be determined by diver observation and by accuracy of closure.

b. Auto-altitude tests - (hovering performance over smooth lake floor or test platform)

- tests of ability to hold altitude
- tests of ability to change altitude on command

Measurement of effectiveness to be determined by diver observation, by repeated sonar depth read outs, and by physical observation of the motion of a tether-line.

c. Auto-altitude tests over rocky bottom

- repeat the two test sequences above
- evaluate performance of averaging algorithm
- orient vehicle over a sharp (45^{o}) dropoff
- evaluate performance of auto-altitude program as a function of vehicle forward speed
- adjust algorithm software as directed by test performance
- plot bottom contour over a straight-line route

d. Auto-altitude tests over sandy bottom

- repeat task sequences in (a & b) above, over the several available lake bottom types

- test vehicle in a pipe-line crossing maneuver
- repeat exercise at 5 altitudes between 4 and 14 feet

e. Maneuvering routines

- maneuver vehicle under operator control through a circle, square, and figure 8 routine
- maneuver vehicle under software control, with tether removed, through same routines

f. Pipe-line following maneuver that

- tests ability to acquire pipeline by:
  1) an instructed intersection with pipeline
  2) software control of a search routine
- pipe-line following test. Measure, by diver observation:
  1) lateral variability in vehicle's course along pipe
  2) effectiveness of course-changing at bends in pipe route
  3) effect of altitude on pipe following performance
  4) vertical purturbations in vehicle course as it follows pipe

C. <u>Test Setup</u>

An experimental test facility has been established on the south side of Diamond Island in Lake Winnipesaukee. On the shore is a cluster of houses with living quarters, an elementary machine shop, and work space for electronics. Docks and moorings are available for the support vessels.

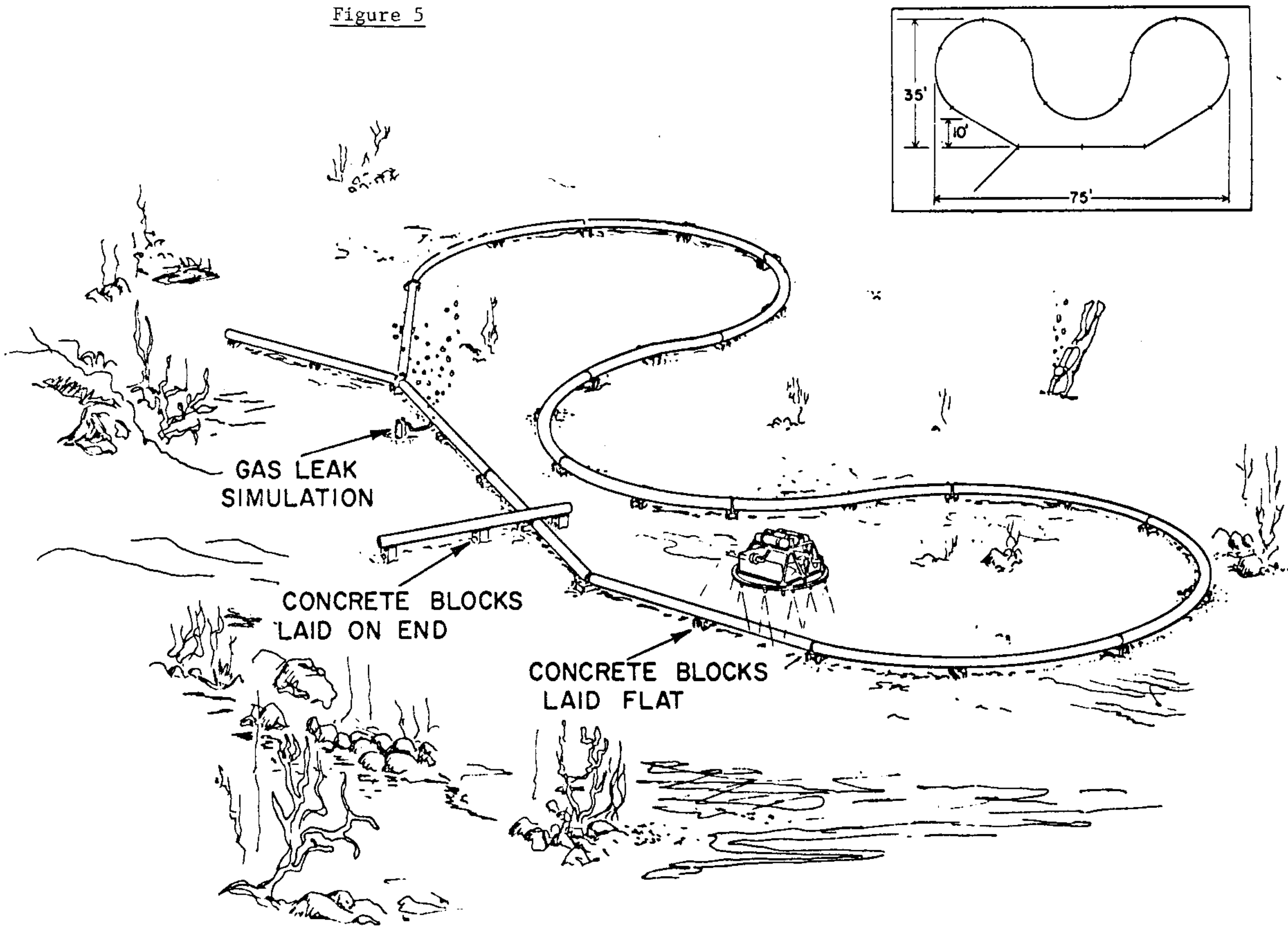
A telephone line, connecting to the University DEC-10 computer, is a key piece of support. The DEC-10 can be employed to load program changes, to supply diagnostic software, and to assemble new microprocessor programs as required.

The lake floor varies from an extremely rocky shoreline of glacial origin to a relatively smooth, sediment-filled bottom. A platform has been built, at a depth of 10 feet, to provide a smooth target for the sonar, and a calibration base for the determination of the effectiveness of the averaging algorithm.

On the lake floor a simulated exposed pipeline has been placed, as described in the Progress Report of January, 1978. The configuration is shown in Figure 5.

The vehicle is supported by a specially designed vessel. This is a catamaran, configured to contain a "well" for launching. A winch is available for vehicle handling. The support vessel has a motor generator for power, and a test bench which supports the Silent 700 terminal used for communication with the vehicle, and assorted test equipment.

Figure 5



TEST PIPELINE

D. Test Results

1. Qualitative Results

The basic philosophy implemented during this operational test period was to perform a step by step evaluation of the pipe-following vehicle system. These tests represented the first real effort to perform open water tests of all of the system components. It was felt necessary to test each of the system components, not only as they related to the pipefollowing task, but also to determine how well they functioned as part of a computer controlled work system.

The results are examined qualitatively on the basis of observed subsystem characteristics, and ability to perform assigned maneuvers, as follows:

a. Sub-Systems Tests

1) The six thrusters responded as required to software command. Six forward and six reverse speeds from $\approx$1000 RPM down to zero were successfully programmed. Simultaneous operation of thrusters were routine. Thruster system time constants were developed to optimize vehicle maneuverability.

2) The Sonar system operated essentially without problem. Each of the 12 beams operated until a failure in one transducer, or its cabling removed it from service. It was paralled by software to an adjacent unit and tests continued.

3) The Sonar Software performed well, providing an excellent test of the data-averaging algorithm.

Changes were made to the averaging algorithm to allow more quickly updated vehicle control.

4) The console containing the data input keyboard and control logic operated without fault. The hard copy - Silent 700, with a bubble memory feature to allow access to non-volatile memory - display terminal proved very effective for operator interfacing. The effectiveness of changing missions by loading in new programs was well demonstrated.

b. Maneuvering Tests

1) The vehicle successfully completed geometric maneuvers of a straight line, a circle, and a square. The planned cubical maneuver was not attempted. These tests were conducted under on-board software control, and could be duplicated by operator control over a tether line.

2) The vehicle successfully hovered over smooth, sandy, and rocky bottoms at various assigned altitudes. Variability in achieved altitude was measured. The vehicle made linear runs while in the auto-altitude mode, and successfully plotted lake bottom contours.

3) The sonar system performed satisfactorily in assessing the angle of the simulated pipeline with respect to the vehicle axis. Appropriate control signals were available to the pipe-following program.

The vehicle, however, failed to follow successfully the pipeline in this test. Time did not permit modification of the software to complete this maneuver. The vehicle repeatedly descended to the bottom, instituted a search for the pipe and after two short a period of time, resurfaced without pipeline acquisition. This maneuver was not performed as written in the computer program, and obviously represented a software error. We were not able to debug it on the site.

c. Other Considerations

The method employed for pressurizing the battery boxes to keep them dry, while submerged, proved inadequate. Tests were terminated on both of the final days by water leaking into the boxes. No other major systematic failure was reported.

2. Quantitative Results

In evaluating the qualitative results, attention is drawn to the environment of the experiment. Since it is a test of an underwater vehicle, of necessity all maneuvers are obscured from view and from ready measurement. Data is generated by:

- visual observation from the surface and by divers
- the accuracy of closure of a maneuver
- the precision of the acoustic measurements which report altitude of each 12 sensors above the bottom
- physical impressions conveyed by measurement of the length and tension on a tether line to the vehicle
- a manned submarine, supplied by New England Ocean Services was available. It, however, proved to be very restricted as an objective measurement tool for test evaluation.

Given these constraints, we report the following results:

a) The thrusters were all exercised through the forward and reverse steps satisfactorily. Interthruster speed measurements agreed generally within 10% over the speed range. Future development could decrease this variability quite substantially.

b) System time constants were developed for the thruster maneuvering routines. These time constants were set up such that for a given vehicle maneuver command, the vehicle would respond in a pre-programmed manner. These maneuvering commands were then accessed by many of the vehicle programs. The time constants were developed to allow the vehicle to turn at three rates. At speed 1, the vehicle will turn 90^o in approximately 30 seconds, at speed 2, 20 seconds, and at speed 3, 10 seconds. Time constants were also determined for rates of descent and ascent.

c) The maneuvers programmed into the vehicle can be judged in substantial part by the closure achieved at the end of the exercise.

The circular program, involving a nominal radius of 35 feet achieved a 360^o path and achieved a closure error that was in the order of two feet or less for a circle of 75 foot diameter. The water current, which would contribute to error, was quite small but was not measured. A similarly dimensioned square figure was performed equally satisfactory, with an error in the order of 5 feet.

d) The sonar system involves a ring of 12 transducers, each pulsed for 50 microseconds at a carrier frequency of 200 kilohertz. The theoretical resolution with a band width is 0.3 inches. Laboratory and field tests gave evidence that the system did indeed resolve to 0.3 inches, and with proper calibration, system accuracy was 1.5 inches over a range of 10 feet.

e) The auto-altitude function of the vehicle performed well after minor changes in the algorithm, which allowed for much more frequent updates of the control system. By taking advantage of a detection window feature in the sonar system, successful measurement of two-way travel time was accomplished using only four values of travel time for the averaging algorithm. Greater variation of the vehicle position was observed when the auto-altitude program was used over a rocky bottom. This response is to be expected.

The purturbations observed in the hovering maneuver depend on a variety of factors including the roughness of the terrain, the signal-to-noise ratio in the sonar, the system gain level (adjustable), the height above the bottom, and the error in the measurement system. In the field experiment, the only effective measurement of hovering purturbations is the data reported by the acoustic sensors, which in turn supply the input to the altitude control system. This data is subject to substantial spatial and time filtering through application of the averaging algorithm which exists in software.

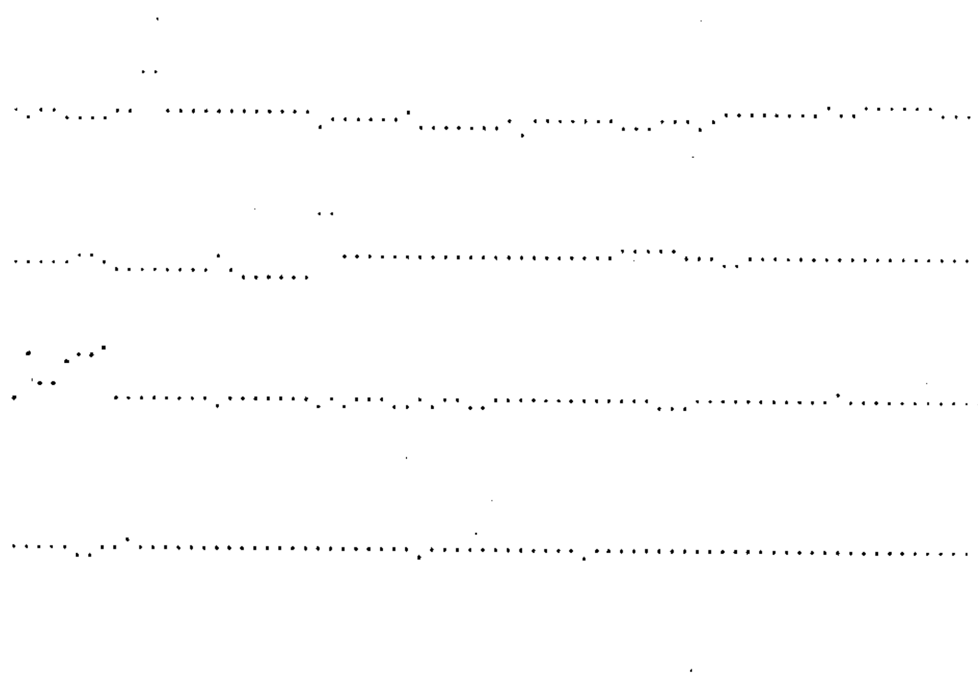
Figures 6 and 7 are printouts of the altitude figure. It is seen here that the stability of the vehicle is well within the needs of the pipefollowing task.

f) The vehicle responded effectively to operator control. It also performed equally well in terms of the stored program in the vehicle memory. Since the memory is limited in size, such operation, free of human operator, is restricted at this stage to simple tasks that fit 3K of memory.

g) The vehicle failed to complete an entire pipefollowing routine. It acquired the pipe and separately accomplished the required maneuvers. A software error was recognized to exist, an error which could not be resolved in the field environment before the termination of the tests.

Following the field operation, further tests at the University located and solved the difficulties. There were indeed two errors in the software executive routine which caused the vehicle to remain on the bottom when it was being controlled by the automatic pipe-following routine. The mistakes have been corrected and the vehicle control system again tested at the University. The vehicle was suspended in a test tank and the simulated pipe moved beneath it. The system successfully performed all of the control responses dictated by the automatic pipefollowing program.

FIGURE 6



Figures 6 and 7 were created to enable us to see how well the vehicle could maintain a constant altitude above the lake bottom. As can be seen from the above profile, the vehicle was able to maintain a fairly constant altitude, with only a few minor fluctuations. It should be noted that the lake bottom used for this profile was fairly flat, and so it is a good indication of the vehicle's ability to maintain a steady altitude.

FIGURE 7

The above profile was taken in an area of the lake where the bottom was covered with large rocks and submerged trees. The large fluctuation seen in the profile was caused by the vehicle passing over these obstacles. Each time the vehicle passed over one of these submerged objects, it would correct its height, in an attempt to maintain a constant altitude.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The vehicle system has successfully demonstrated the essential characteristic of autonomy - self-controllability - by performing simple interrelated tasks without intervention by a remote-located operator.

Experience gained to date has helped to answer some basic questions concerning the eventual use of autonomous, free-swimming submersibles. Also, it has shown that the capability to use these vehicles in performing preprogrammed underwater tasks is within current limits of available technology. The pertinent technologies are not prohibitive in cost or complexity. In particular, advances in microcomputers have permitted the development of sophisticated control concepts with rather unsophisticated hardware implementation. As microcomputer technology advances, the tasks performed by autonomous vehicles will be constrained mainly by the software system used to implement the necessary control concepts, and here there is little limitation in sight.

A. At the end of the first year's program, we draw the following conclusions:

    1. The UNH vehicle, this year, became autonomous, operating with an effective on-board intelligence capable of responding in appropriate ways to instruments which sensed one facet of its environment; - distance above the bottom.

    2. The vehicle performed a repertoire of tasks, defined in on-board memory, without the guidance of the remote operator.

3. The operating routines, stored in memory, were easily changed at will through a serial data port.
4. It was demonstrated that sophisticated tasks occupy only a small portion of the available memory space. The scope of the potential tasks that the vehicle might assume, appears to not be limited by computer memory constraints. This has important implications for the application of the vehicle to wide-ranging set of tasks. Moreover, this intelligence is available at a cost which continues to decrease.
5. The vehicle, which started as a hardware device, is quickly changing, and is becoming dominated by software considerations. This evolutionary trend, apparent in all advanced ocean-engineering programs, has major implications to future program planning.

B. We have developed some insights into unmanned, untethered submersibles which are worthy of consideration as they relate to the on-going program.

1. The potential of a low-cost unmanned, untethered inspection vehicle has been reinforced strongly during this year's work.
2. The value of the unmanned, untethered vehicle is seen to be highest:
   - when the working area is deeper than divers can economically serve.
   - when a high degree of danger make diver risk intolerable.

- when interior regions of structures must be examined, and risk of entanglement precludes tethered systems.
- when mission durations are relatively limited, and the task involves light weight sensors, the untethered vehicle appears to compare favorably in cost and effectiveness with operating and servicing a tethered vehicle.

3. The ideal role for the crab-like 5-degree of freedom platform is a three-dimensional task. It could best serve pipe-line surveys by, for example, examining faulty valves or possibly pipe-line cross-overs from various perspectives. The apparent true value of the 5-degree of freedom vehicle, as described in this report, lies in obtaining multi-dimensional descriptions of points of interest. It is particularly useful in the instrumentation and description of structures, as opposed to pipe-line and bathymetric surveying.

C. As part of its broad objective, the project has also brought into focus some specific problem areas which will need to be addressed in furthering the development of autonomous, free-swimming vehicles.

1. The characteristic of autonomy forces much effort to be placed on the development of control algorithms and the necessary testing of these algorithms under

operational conditions. Future development efforts should require a large part of the total effort to be spent in field testing in order to refine the control algorithms.

2. The implicit usefulness of the microprocessor controller is limited by the sensory inputs it receives. It must be aware of the relative positions of its base, its work area, and itself, and in addition it must perceive its heading. Specific sensors, peculiar to the task assigned must be available and these may include many differing types. A key area needing attention, therefore, is the adaptation of presently available sensor systems to the needs of the vehicle.

3. The system must be able to communicate, to derive new operational commands, and to report its status to the supervisory operator.

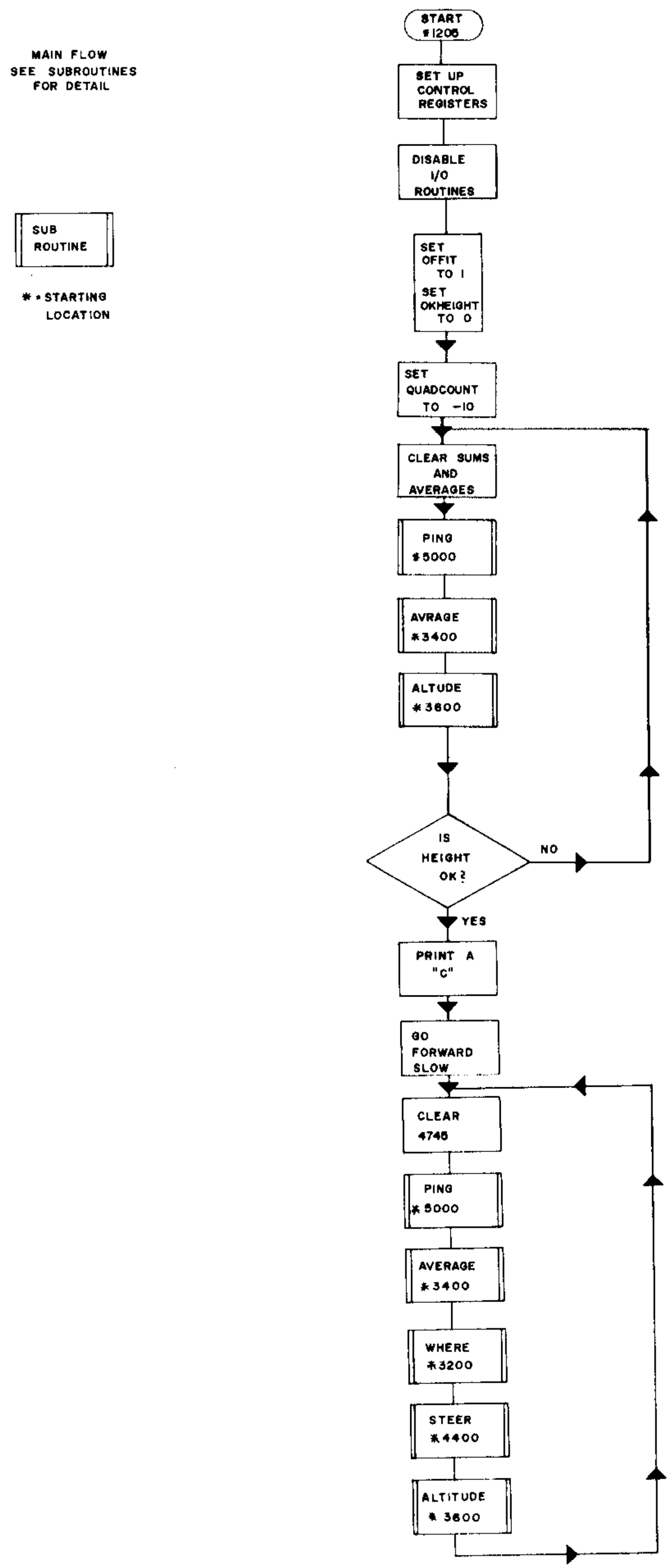
We conclude that, in one sense - the historical one, the placing of intelligence plus sensors on a small vehicle aimed at accomplishing a dedicated mission, is a major achievement. In a larger sense it is not, for the rapid development of solid state devices so clearly marks the broad road ahead that the efforts of the past year look limited indeed. We know, almost apriori, that the vehicle can do "anything" we ask of it. The problems now are the ancient ones, those of interfacing a new device with the realities of the ocean working environment. As pointed out in the Technology Development Plan, the emphasis should be placed on sensing the vehicle's interface with the work station, and on systems to communicate, and to navigate. We have demonstrated in this year's program that the challenge is not in getting an effective on-board intelligence on the inspection vehicle, but in servicing it, in permitting it to function effectively, and in bringing its acheivements back into the consciousness of the operator.

APPENDIX A

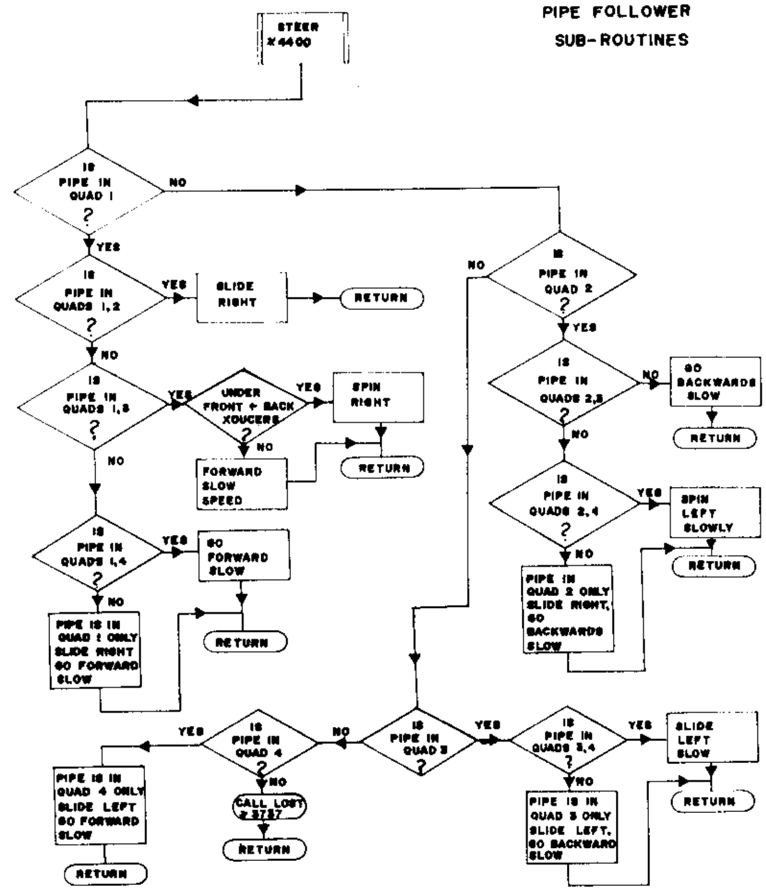
FLOWCHARTS:

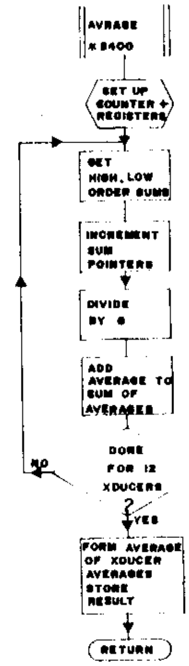
AUTONOMOUS VEHICLE SOFTWARE SYSTEM

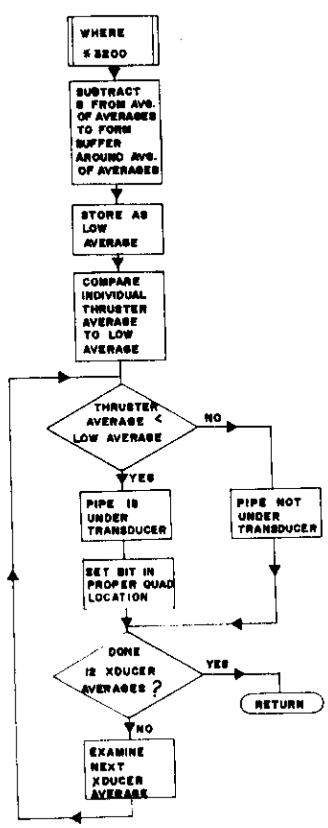
PIPE FOLLOWER

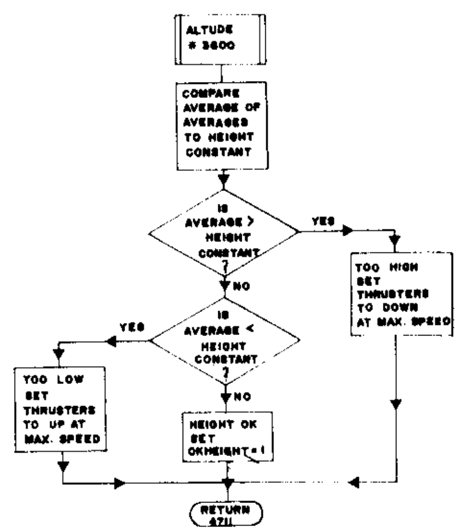


PIPE FOLLOWER SUB-ROUTINES

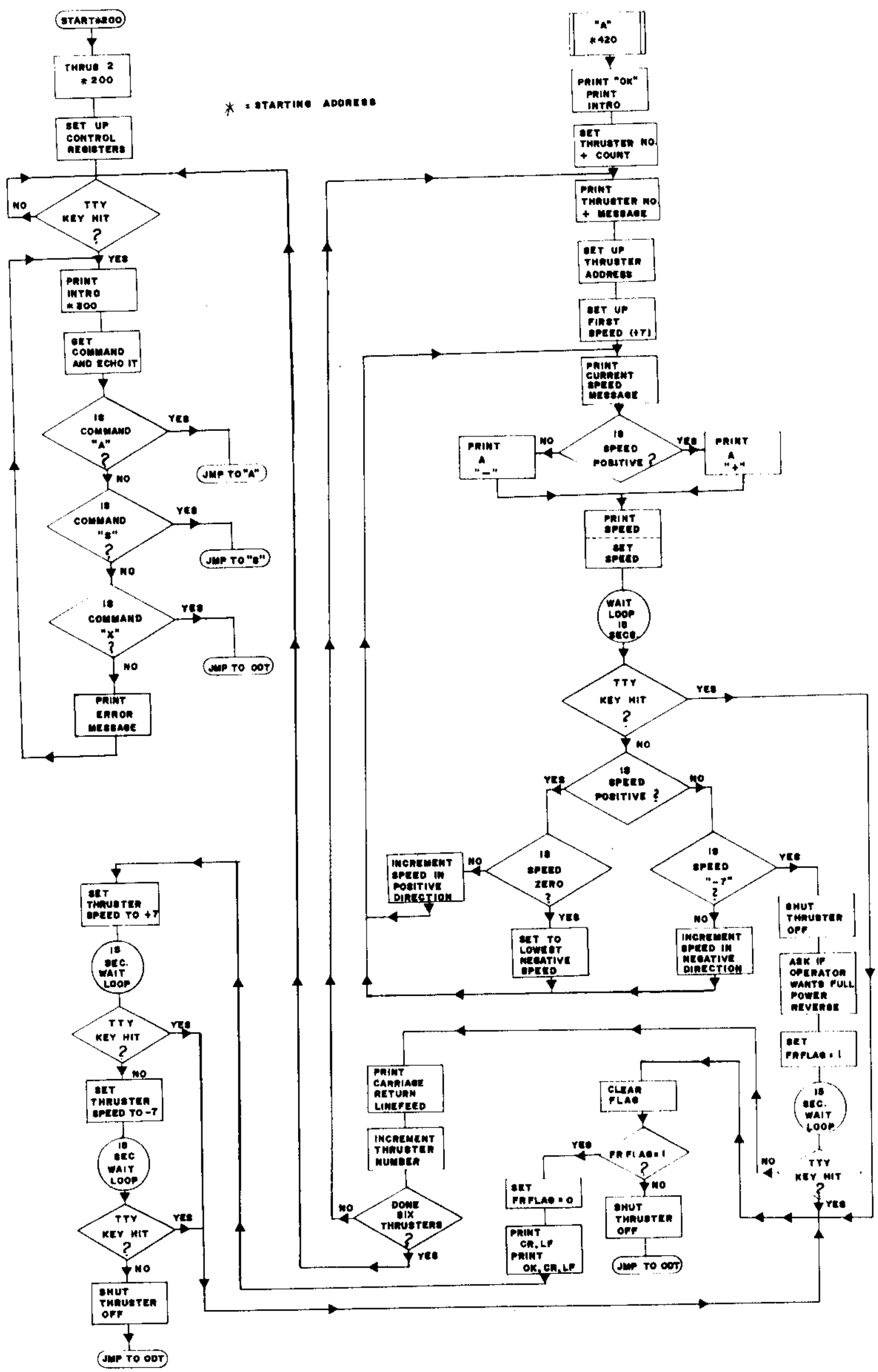




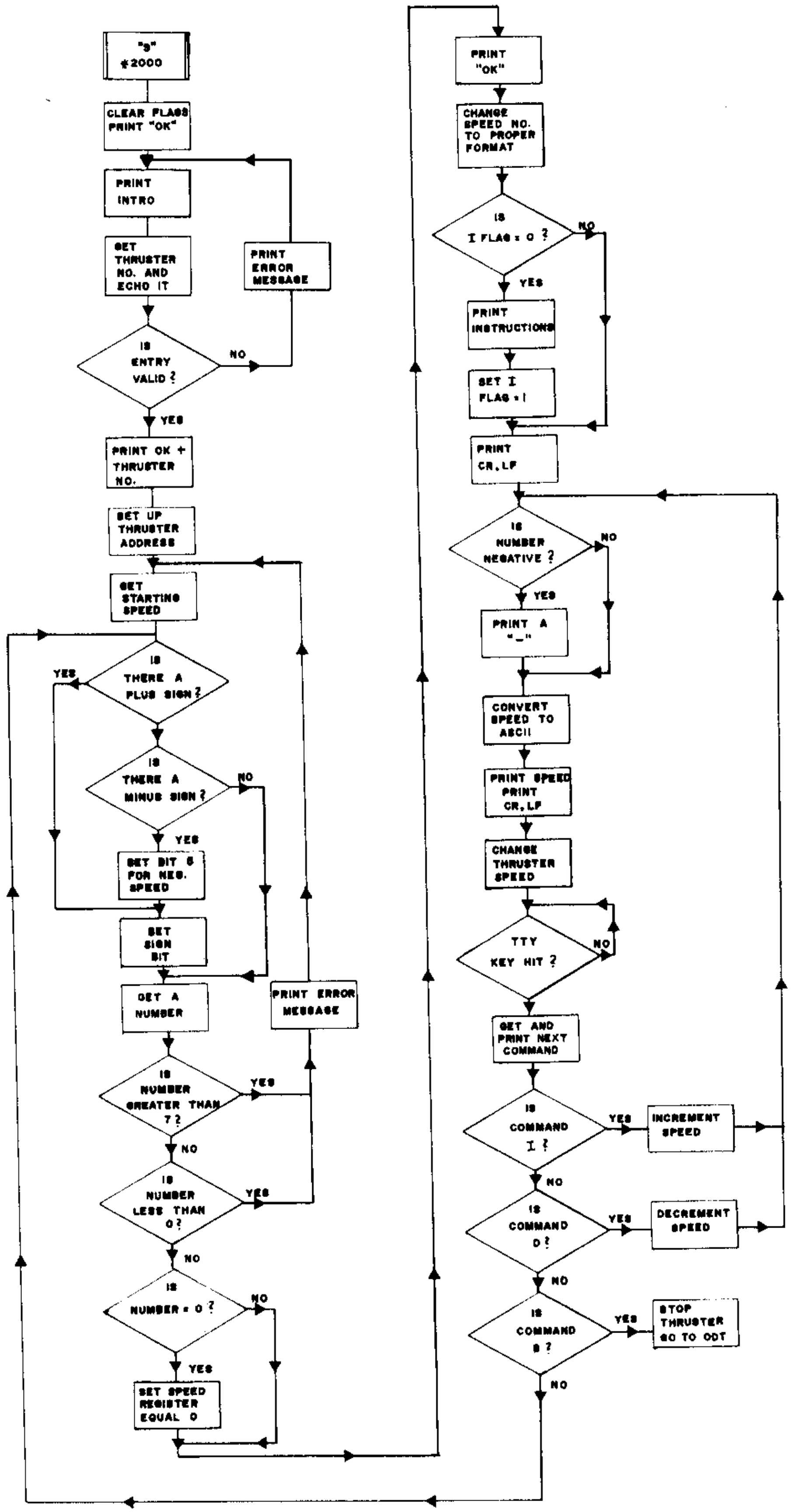


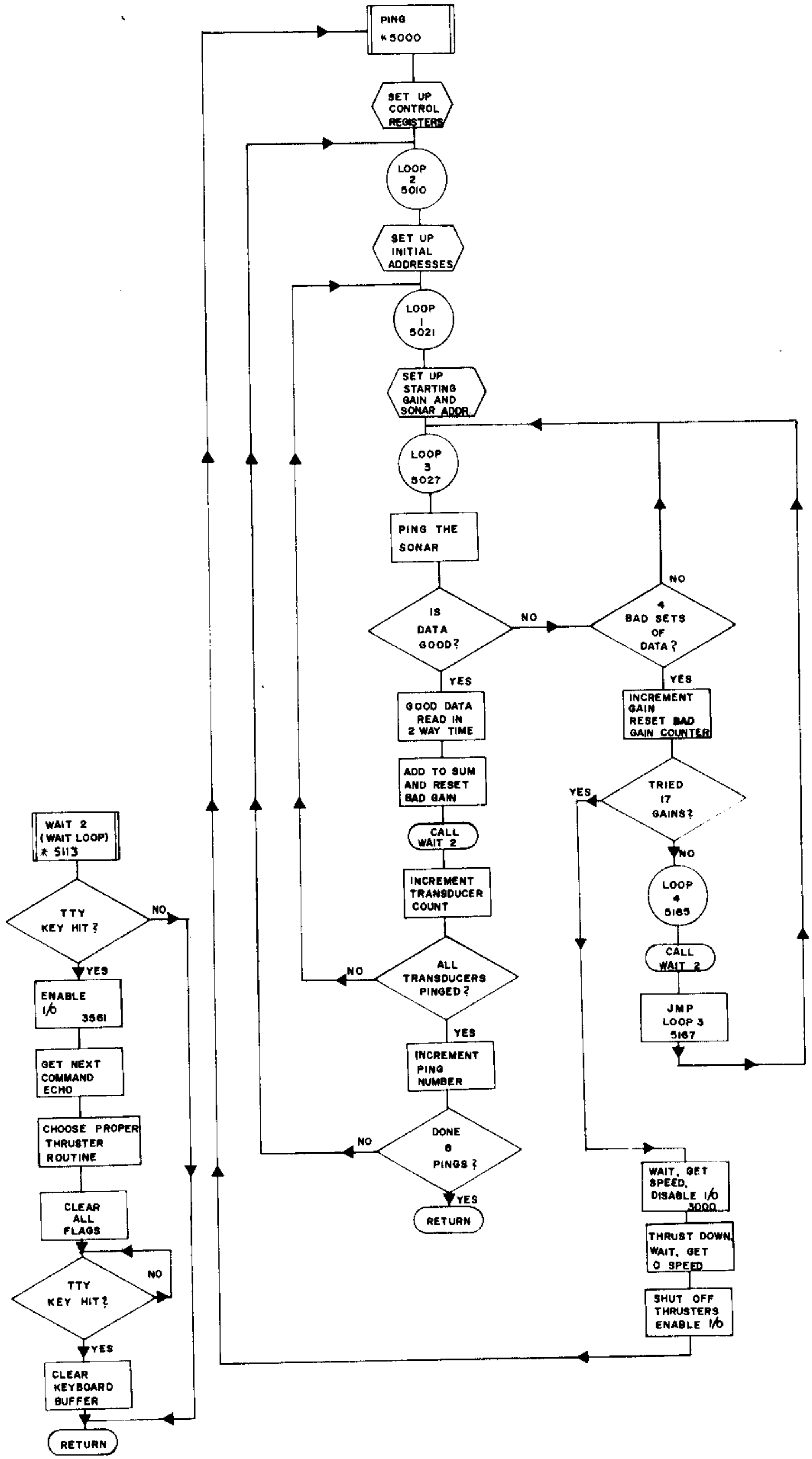


THRUSTER INTERACTIVE DIAGNOSTIC ROUTINE

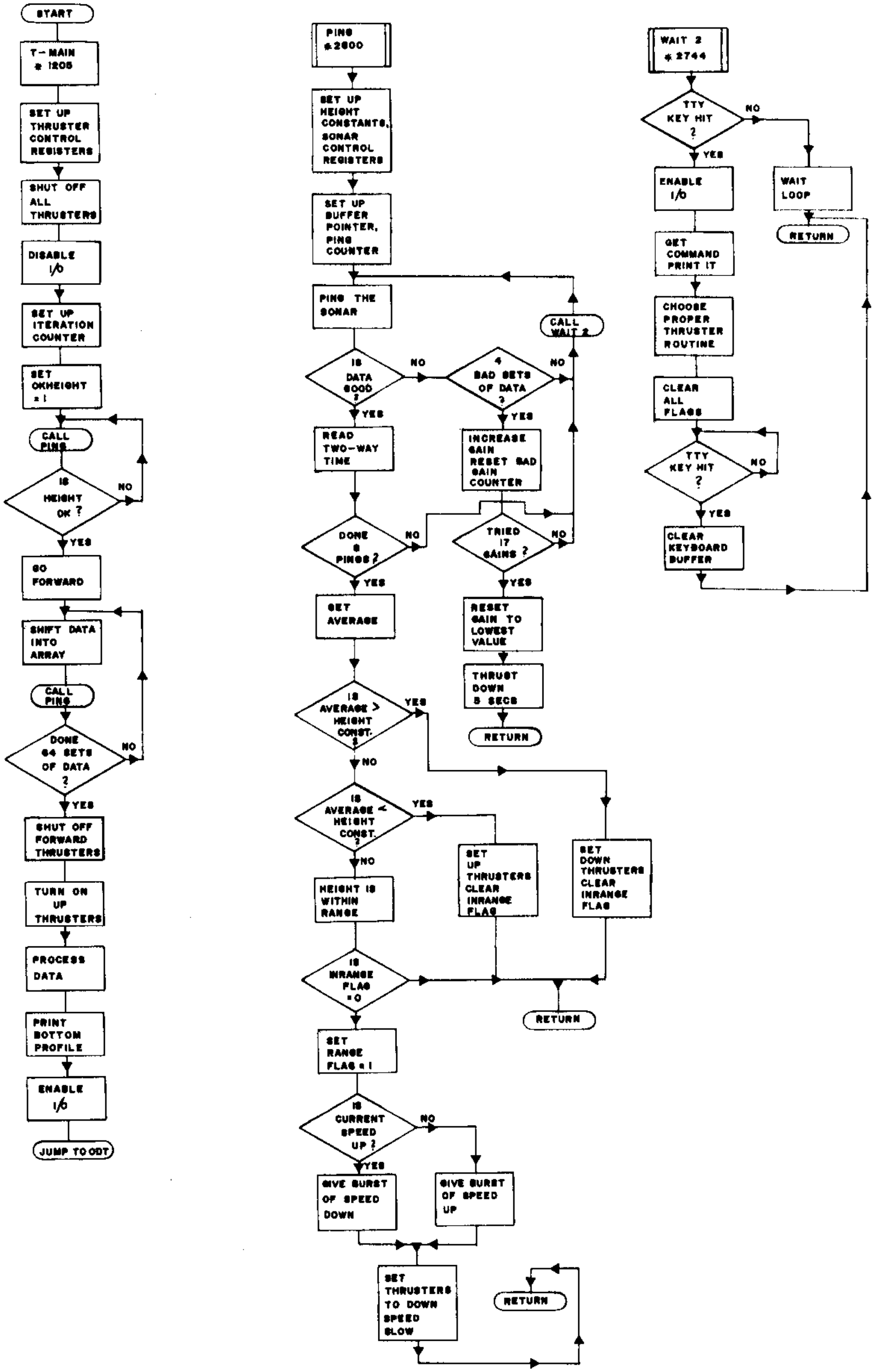


THRUSTER INTERACTIVE DIAGNOSTIC ROUTINE

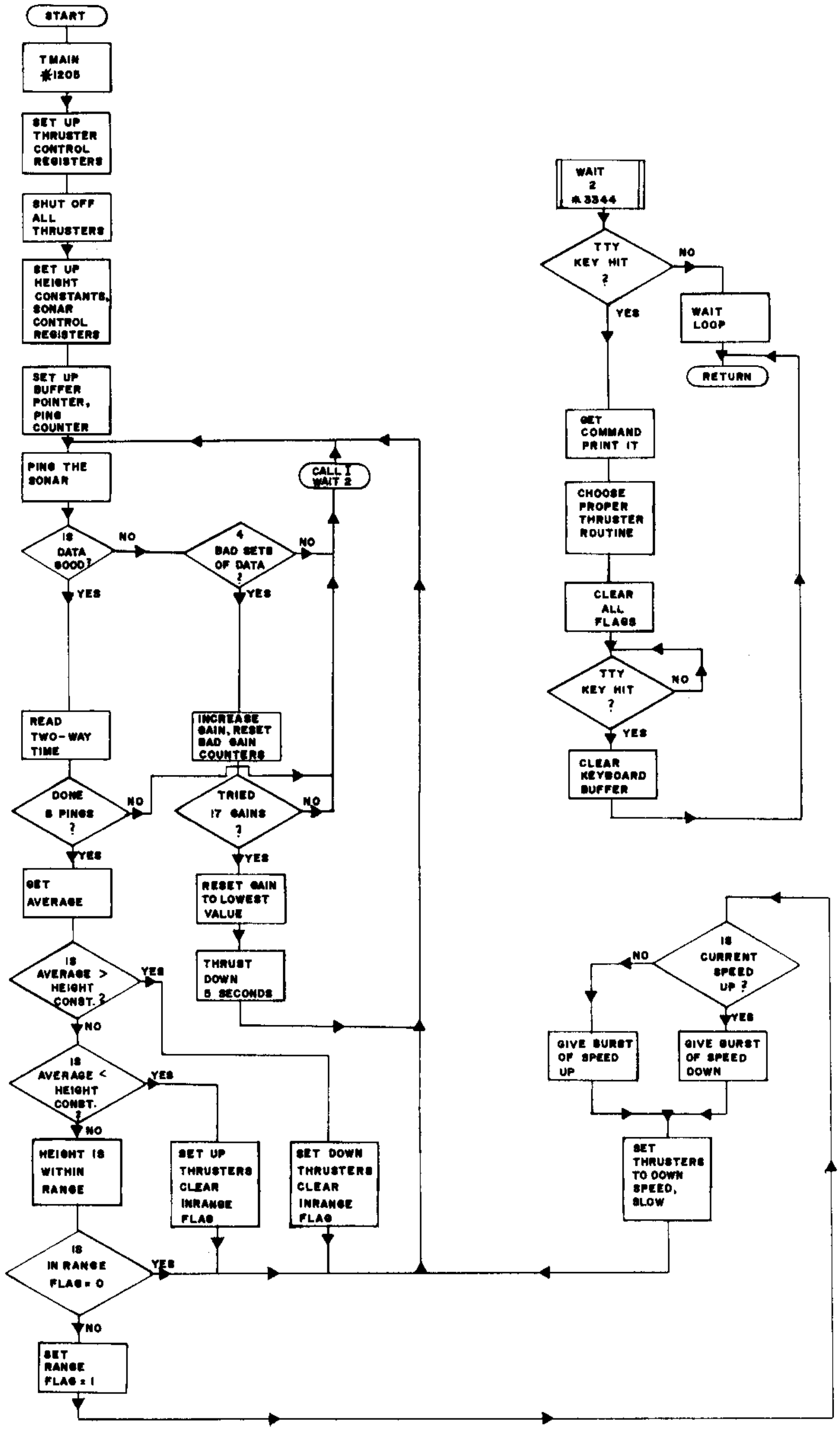



PING
*5000
SET UP CONTROL REGISTERS
LOOP 2 5010
SET UP INITIAL ADDRESSES
LOOP 1 5021
SET UP STARTING GAIN AND SONAR ADDR.
LOOP 3 5027
PING THE SONAR
IS DATA GOOD?
NO
YES
4 BAD SETS OF DATA?
NO
YES
GOOD DATA READ IN 2 WAY TIME
ADD TO SUM AND RESET BAD GAIN
CALL WAIT 2
INCREMENT TRANSDUCER COUNT
ALL TRANSDUCERS PINGED?
NO
YES
INCREMENT PING NUMBER
DONE 8 PINGS?
NO
YES
RETURN
INCREMENT GAIN RESET BAD GAIN COUNTER
TRIED 17 GAINS?
YES
NO
LOOP 4 5165
CALL WAIT 2
JMP LOOP 3 5167
WAIT, GET SPEED, DISABLE I/O 3000
THRUST DOWN, WAIT, GET 0 SPEED
SHUT OFF THRUSTERS ENABLE I/O
WAIT 2 (WAIT LOOP) * 5113
TTY KEY HIT?
NO
YES
ENABLE I/O 3561
GET NEXT COMMAND ECHO
CHOOSE PROPER THRUSTER ROUTINE
CLEAR ALL FLAGS
TTY KEY HIT?
NO
YES
CLEAR KEYBOARD BUFFER
RETURN

TRACKLINE PRINTOUT PROGRAMS



MANEUVERING PROGRAMS WITH AUTO ALTITUDE



APPENDIX B

The Task Statements below describe the Project Goals established at the start of the contract year.

Five project goals have been defined for the period of September 1, 1977 through August 31, 1978.

1. Develop operationally reliable hardware and software by combined changes in packaging and interface control.
2. Develop a vehicle control console through which the various vehicle functions are easily implemented. Implement the control functions, through the tether cable, at a data rate which could be duplicated by an acoustic data link.
3. Develop the necessary hardware and software to make external access to the on-board microcomputer possible.
4. Perform a total evaluation of the first generation pipe follower vehicle to determine its limitations and what can be done to minimize these limitations, and document the vehicle and the test results in a manner which would allow easier development of a possible second generation vehicle.
5. Develop a technology sharing system between the Naval Ocean Systems Center and the University of New Hampshire.

The following paragraphs describe in more detail the development goals of this project.

1. Operationally Reliable Hardware and Software

It is proposed to make changes in existing software which would allow a fail-safe system to automatically re-enter a program into the microcomputer if the original program is lost or altered. This system will act as a "watchdog program" for the microcomputer. The interface hardware will also be changed to allow more efficient use of the programming structure and make the total design much more flexible in terms of future programming changes. Packaging of the electronics within the vehicle is very important in terms of overall system reliability. There are changes which will be made in both the microcomputer packaging and the sonar system packaging.

2. Vehicle Control

During many of the testing procedures it will be necessary to control the vehicle through an operator console which is attached to the vehicle via a tether cable. Since the vehicle has such a high maneuverability (six thrusters) it is necessary to develop this console in order that an operator may easily perform complex vehicle maneuvers. It is intended that the control signals required to perform the maneuvers be of a data rate which is slow enough that the tether cable could eventually be replaced by an acoustic data link.

3. External Access to On-Board Microcomputer

With a vehicle of this type it will be necessary to have external control over the microcomputer functions. This control will be implemented through the use of an external terminal which can control all functions. This will allow in-field software control without the need of opening pressure cases.

In order to obtain this type of control, a hardware system will be developed to act as the terminal interface with the computer. It is intended that the field terminal will have the capability of being randomly connected to the vehicle without causing detrimental effects to either the hardware or software of the on-board microcomputer.

4. Total Evaluation

During the development of this vehicle, it will not be possible to use results of previous vehicle developments of this type since they do not exist. It then becomes very necessary to learn as much as possible during the development of the first vehicle. It is proposed that a very careful and complete testing program be performed which will obtain as much information as possible for further design efforts on this type of vehicle.

The test program will include simulated test runs over various configurations of a 8" pipeline, which will be placed on the bottom of a lake where the University of New Hampshire maintains a testing facility. During these tests, it is intended to document the results as quantitatively as possible through the use of underwater television and/or movies of the vehicle.

5. Technology Sharing

It is felt that substantial benefits will be derived by sharing technology on free-swimming vehicles between University of New Hampshire and the Naval Ocean Systems Center. Such an approach has the potential of bringing about an exchange of both knowledge and equipment during the project duration.

In summary, it is proposed to develop an interaction between the Naval Ocean Systems Center and the University of New Hampshire which would be to the mutual benefit of both groups, and allow a vehicle development consistent with the goals of Naval Ocean Systems Center in this area.